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MEMORANDUM No. 31

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HYPERSONIC RESEARCH PROJECT

Memorandum No. 31

February 1, 1956

INVISCID HYPERSONIC FLOW OVER BLUNT-NOSED SLENDER BODIES

by

Lester Lees

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TECHNICAL REPORT



ARMY ORDNANCE CONTRACT NO. DA-04-495-Ord-19

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Pasadena, California

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Clark B. Millikan, Director
Guggenheim Aeronautical Laboratory

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SUMMARY

At hypersonic speeds the drag/area of a blunt nose is much larger than the drag/area of a slender afterbody, and the energy contained in the flow field in a plane at right angles to the flight direction is nearly constant over a downstream distance many times greater than the characteristic nose dimension. The transverse flow field exhibits certain similarity properties directly analogous to the flow similarity behind an intense blast wave found by G. I. Taylor and S. C. Lin. Conditions for constant energy show that the shape of the bow shock wave $R(x)$ not too close to the nose is given by $R/d = K_1(\gamma) \left(\frac{x}{d}\right)^{\frac{1}{2}}$ for a body of revolution, and by $R/d = K_0(\gamma) \left(\frac{x}{d}\right)^{2/3}$ for a planar body, where d is nose diameter, or leading-edge thickness. A comparison with the experiments of Hammitt, Vas, and Bogdonoff on a flat plate with a blunt leading-edge at $M_\infty = 13$ in helium shows that the shock wave shape is predicted very accurately by this analysis. The predicted surface pressure distribution is somewhat less satisfactory.

Energy considerations combined with a detailed study of the equations of motion show that flow similarity is also possible for a class of bodies of the form $r_b \sim x^m$, provided that $m' \leq m \leq 1$, where $m' = 3/4$ for a planar body and

$$m' = \frac{3/2(\gamma + 1)}{3\gamma + 2}$$

for a body of revolution. When $m < m'$ the shock shape is not similar to the body shape, and except for the constant energy flows the entire flow field some distance from the nose must depend to some extent on the details of the nose geometry.

By again utilizing energy and drag considerations one finds that at hypersonic speeds the inviscid surface pressures generated by a blunt nose are larger than the pressures produced by boundary layer growth on a flat surface over a distance from the nose of order l , where

$$l/d \approx \frac{1}{15} \left(\frac{Re_d}{M_\infty^2} \right)^3 .$$

(Here Re_d is free-stream Reynolds number based on leading-edge thickness.)

Thus at $M_\infty = 15$ the viscous interaction effects should be important for $Re_d < 10^3$, but somewhere in the range $1500 < Re_d < 2000$ the inviscid effects must spread rapidly over the plate surface, and certainly for $Re_d > 3000$ the inviscid pressure field is dominant and determines the boundary layer development, skin friction and heat transfer over the forward portion of the body. These rough estimates are in qualitative agreement with the experimental results of References 7 and 9.

LIST OF SYMBOLS

Free stream quantities are denoted by the subscript " ∞ ", while the subscript "b" denotes quantities evaluated at the body surface.

a sound speed

A constant

C Chapman-Rubens factor in relation $\frac{\mu}{\mu_{\infty}} = C(T/T_{\infty})$

C_p pressure coefficient, $\frac{p - p_{\infty}}{\frac{1}{2} \rho_{\infty} U_{\infty}^2}$

d nose diameter or leading-edge thickness

D drag

E energy in transverse flow field

$F(z)$ $\frac{p(z)}{\rho_{\infty} v_s^2}$

k geometric index

l influence length

L body length

m exponent, $r_b \sim x^m$

M Mach number, u/a

p pressure

Q any physical quantity

r distance normal to body axis or chord line (x- axis)

R distance of shock wave from x- axis

Re_d Reynolds number, $\frac{\rho_{\infty} U_{\infty} d}{\mu_{\infty}}$

t	time
T	absolute temperature
u, v	velocity components parallel and normal to x - axis
v_s	shock velocity in direction normal to x - axis, $U_\infty \frac{dR}{dx}$
x	distance along body axis or chord line, measured from forward stagnation point
z	r/R
α	exponent, $\frac{1-m}{m}$
γ	ratio of specific heats, C_p/C_v
θ_s	shock angle with respect to x - axis
μ	absolute viscosity
ρ	density
τ	$r_{b \max}/L$
$\bar{\Phi}(z)$	$\frac{v(z)}{v_s}$
$\Psi(z)$	$\rho(z)/\rho_\infty$

1. Introduction

When a finite amount of energy is suddenly released at some "point" in a gas initially at rest, G. I. Taylor¹ showed that the radius of the intense spherical blast wave generated by the explosion grows like

$$R = F_1(\gamma) \left(\frac{E}{\rho_\infty} \right)^{1/5} t^{2/5}.$$

The flow field in the wake of the shock wave exhibits a certain similitude, in the sense that the pressure, density, and outflow velocity are described by relations of the form

$$\frac{Q(r)}{Q(R)} = f\left(\frac{r}{R}\right).$$

This similarity holds only in the intermediate zone not too close to the origin of the explosion, (where the theory predicts that $T \longrightarrow \infty$ and $p \longrightarrow 0$), yet not so far away that the shock strength has decayed to a level where the strong shock approximations are no longer applicable. Taylor's analysis was later extended to the case of a cylindrical blast wave by S. C. Lin², who found that

$$R = F_2(\gamma) \left(\frac{E}{\rho_\infty} \right)^{1/4} t^{1/2}$$

in this case. Lin also remarked that according to Hayes'³ concept of hypersonic similitude this relation for $R(t)$ should describe the shape of the bow shock wave behind an unyawed, axially-symmetric body travelling at a uniform hypersonic velocity. The axial flow velocity is nearly constant, provided that the shock angle θ_s is not too large, and the flow in a transverse plane fixed in space behind the body resembles the flow generated by the explosion of a long highly-concentrated cylindrical charge at the time $t = 0$. Here $t \longrightarrow \frac{x}{U_\infty}$, and the energy E

per unit length of charge is identified with the total drag of the body.

The purpose of this note is to point out that these considerations are equally applicable to the shock wave generated by a blunt nose of finite radius on an unyawed slender body. At hypersonic speeds the drag of the nose per unit cross-sectional area is much larger than the drag/area of an afterbody with a uniformly small slope in the meridian plane. To be specific, the drag of a blunt nose of diameter d (or leading-edge of thickness d , for a planar body) is given by

$$D_N \approx \frac{1}{2} \rho_\infty U_\infty^2 d^{k+1}$$

while the drag of a conical (or wedge-like) afterbody of half-angle θ and length L , for example is \sim

$$\frac{1}{2} \rho_\infty U_\infty^2 (\theta^2) (\theta L)^{k+1}$$

where $k = 0$ for a planar body and $k = 1$ for a body of revolution. The drag of the afterbody becomes comparable with the nose drag only when

$$\frac{L}{d} \sim \frac{1}{\theta^{\frac{k+3}{k+1}}}$$

In other words, the shape of the bow shock wave, the inviscid flow field and the surface pressure distribution on a slender body are dominated by the blunt nose or leading-edge over a downstream distance many times greater than the characteristic nose dimension. The analogy with a constant-energy, non-steady similar flow of the type investigated by Taylor and Lin is complete for the particular case of a blunt nose followed by a cylindrical afterbody ($\theta = 0$). In this case the shock shape is described by

$$R \sim \left(\frac{\frac{1}{2} \rho_{\infty} U_{\infty}^2 d^2}{\rho_{\infty}} \right)^{1/4} \left(\frac{x}{U_{\infty}} \right)^{\frac{1}{2}}, \text{ or } R/d = K_1 (\gamma) \left(\frac{x}{d} \right)^{\frac{1}{2}}.$$

As shown below, the analogy is readily extended to planar bodies, where it is complete for the case of a flat surface with a blunt leading-edge at zero angle of attack. These rough considerations suggest that it would also be worthwhile to investigate the more general case in which the energy of the transverse flow is increasing with distance from the nose, but the shape of the body is such that flow similarity is preserved. The corresponding non-steady flow problems are the expanding sphere, expanding cylinder, and motion of a piston in a long, straight tube.

2. Similar Flows: Energy and Drag Considerations

Taylor's assumption of flow similarity in a fixed transverse plane is satisfied only for "strong" shocks, where

$$v(R) \approx \frac{2}{\gamma+1} v_s, \quad \frac{p(R)}{\rho_{\infty}} \approx \frac{2}{\gamma+1} v_s^2, \quad \text{and} \quad \frac{\rho(R)}{\rho_{\infty}} \approx \frac{\gamma+1}{\gamma-1}.$$

The strong shock approximation in turn is applicable only when

$$\frac{\gamma-1}{2} \frac{v_s^2}{a_{\infty}^2} = \frac{\gamma-1}{2} M_{\infty}^2 \theta_s^2 \gg 1. \quad *$$

In addition,

$$v(R) \sim R^{-a}, \text{ or } R^a \frac{dR}{dt} = A (\text{const.}), \text{ and } R = \left(\frac{A}{U_{\infty}^m} \right)^{\frac{1}{m}} x^{\frac{1}{m}}$$

where

$$a = \frac{1-m}{m}.$$

* Previous experience with hypersonic similarity suggests that this approximation is useful when

$$\frac{\gamma-1}{2} M_{\infty}^2 \theta_s^2 > 2 \longrightarrow 3.$$

Also, the boundary condition $v(r_b) = U_\infty \frac{dr_b}{dx}$ on the body requires that $v(r_b) = z_b v_s$, or $z_b = \frac{r_b}{R} = \text{const.}$ if flow similarity is to exist; i. e., $r_b \sim x^m$, and the shock and body are similar.

When these conditions are satisfied, we may write

$$v(r, t) = A \frac{\Phi(z)}{R^a}, \quad \frac{p(r, t)}{\rho_\infty} = A^2 \frac{F(z)}{R^{2a}}, \quad \text{and}$$

$$\frac{p(r, t)}{\rho_\infty} = \Psi(z), \quad \text{where } z = r/R \quad (\text{Fig. 1}), \quad \text{and the energy } E$$

associated with the flow field in a transverse plane is expressed as follows:*

$$(1) \quad E = z^k \pi^{k'} \int_{r_b}^R \rho \left(c_v T + \frac{v^2}{2} \right) r^k dr, \quad \text{or}$$

$$(1a) \quad E = z^k \pi^{k'} \rho_\infty A^2 R^{k+1-2a} \int_{z_b}^1 \left(\frac{F}{\gamma-1} + \frac{1}{2} \Psi \Phi^2 \right) z^k dz,$$

where $k = k' = 0$ for planar flow; $k = k' = 1$ for axially-symmetric flow; $k' = 1$ and $k = 2$ for non-steady spherical flow. An energy balance shows that

$$(2) \quad \frac{dE}{dt} \equiv U_\infty \frac{dE}{dx} = z^k \pi^{k'} r_b^k p_b v_b; \quad \text{in other words, the}$$

energy of the fluid motion changes at a rate given by the rate at which work is done by the pressure forces acting on the fluid along the body surface. Evidently from Eq. (1a), $E = \text{const.}$ when $2a = 1 + k$, or

$$m = \frac{2}{3+k}, \quad \text{and by Eq. (2) } v_b = z_b = 0 \text{ everywhere, except right at}$$

* The quantity E has the dimensions of energy/area for planar flows, energy/length for axially-symmetric (cylindrical) flows, and the energy itself for non-steady spherical flows.

the nose. For spherical flow $\alpha = 3/2$, $m = 2/5$, and $R \sim t^{2/5}$ (Taylor¹); for axially-symmetric flow $\alpha = 1$, $m = \frac{1}{2}$, and $R \sim x^{\frac{1}{2}}$ (Lin²); for planar flow $\alpha = \frac{1}{2}$, $m = 2/3$, and $R \sim x^{2/3}$. Also, when $2\alpha < 1 + k$, or $m > \frac{2}{3+k}$, then $\frac{dE}{dt} > 0$, and $v_b > 0$, $z_b > 0$. For a positive body slope (or an expanding sphere, cylinder, or piston), similar solutions exist (if at all) only for $m > \frac{2}{3+k}$. * The same conclusion is reached by considering the pressure drag. For these bodies,

$$D = 2^k \pi^{k'} \int_0^L r_b^k p_b \left(\frac{dr_b}{ds} \right) ds = \text{const.} \int_0^R R^{k-2\alpha} dR ,$$

or

$$D = \text{const.} \left\{ R^{k+1-2\alpha} \bigg|_0^R \right\} ; \quad \text{the drag is finite only when } m \geq \frac{2}{3+k} .$$

These conditions for the existence of similar solutions are necessary but not sufficient ones. A study of the mathematical properties of the equations of motion shows** that except for the special case $m = \frac{2}{3+k}$, non-singular similar solutions exist only when $m' \leq m \leq 1$, where $m' = 3/2 \frac{\gamma + 1}{\gamma(2+k) + 2}$. For planar flow $m' = 3/4$,

* Stewartson⁴ also found the restriction $m > 2/3$ in his study of boundary-layer shock-wave interaction over a planar body of shape $r_b \sim x^m$. For $m < 2/3$ the lateral velocity given by the inviscid solution at the outer edge of the boundary layer is negative, and he was unable to match it with the positive (outward) lateral velocity given by the sum of the body slope and the boundary layer growth. However, no explanation was offered for this behavior, and the special significance of the case $m = 2/3$ was not explored.

** A detailed analysis is contained in a forthcoming GALCIT Hypersonics Technical Report.

independently of γ ; for axially-symmetric flow $m' = 0.59$ for $\gamma = 1.2$, $m' = 0.58$ for $\gamma = 1.4$, and $m' = 0.57$ for $\gamma = 5/3$. Included within this range of values of m are of course the wedge and cone ($m = 1$), and also the "hypersonic optimum shape" $r_b \sim x^{3/4}$, or body of revolution of minimum zero-lift drag for a given fineness ratio, as determined from Newtonian impact theory neglecting centrifugal force by Eggers, Dennis, and Resnikoff⁵. By including centrifugal force, J. D. Cole⁶ obtained the value $m = 2/3$ for this optimum shape. For planar flow Cole obtains an optimum shape with $m = 0.87$; both of his cases also lie within the range $m' \leq m \leq 1$.

When these similar solutions do exist one expects them to provide a good approximation to the pressure and velocity fields not too close to the blunt nose. The surface pressure distribution (for example) is given by

$$\frac{p(r_b)}{p_\infty} = \frac{m^2}{z_b^2} F(z_b) \tau^2 \frac{M_\infty^2}{\left(\frac{x}{L}\right)^{2(1-m)}}, \quad \text{or}$$

$$C_p(r_b) = \frac{2m^2}{z_b^2} F(z_b) \tau^2 \bigg/ \left(\frac{x}{L}\right)^{2(1-m)}, \quad * \quad \text{where } \tau = \frac{r_{b \max}}{L},$$

For these bodies, the results obtained by utilizing any one of the purely "local" hypersonic approximations, such as tangent-wedge (or cone), or Newtonian plus centrifugal force, are similar in form, which gives one some confidence in these approximations, provided that $m > m'$.

* Here $F(z_b)$ are functions of m and γ ; their values are now being determined for a few cases of interest.

When $m < m'$, however, we conclude that the shock shape is not similar to the body shape, and (except for the special case $m = \frac{2}{3+k}$) the entire flow field some distance from the nose must depend to some extent on the details of the nose geometry. It remains to be seen whether any simple local hypersonic approximation is applicable to a blunt-nosed slender body in these cases.

3. Comparison Between Theory and Experiment for a Flat Plate with a Blunt Leading-Edge

A clear test of the analogy between hypersonic flow over a blunt-nosed slender body and the constant-energy Taylor-type flow is provided by the experimental investigation carried out by Hammitt, Vas, and Bogdonoff⁷ on a flat plate in the Princeton helium tunnel. The blunt leading edge is formed by taking a plane cut normal to the upper plate surface, which is parallel to the oncoming flow. The lower surface is inclined at 10° to the flow, but does not influence the upper surface. In these tests the Mach number ranges from 11.4 to 13.8, and the shock angles are such that the assumptions of the strong shock theory are fully satisfied. Shock wave shapes were determined from interferograms over a range of leading-edge thicknesses

$$0.17 \times 10^{-3} \text{ in.} \leq d \leq 59 \times 10^{-3} \text{ in.}, \text{ or } 120 \leq Re_d \leq 70.6 \times 10^3.$$

For $Re_d > 16 \times 10^3$ viscous effects are negligible (see below), and the empirical fit to the data presented in Ref. 7 is $R = 1.36 d^{0.34} x^{0.66}$, which is reasonably close to the theoretical prediction $R = K_0(\gamma) d^{1/3} x^{2/3}$ in this case. (See Fig. 2) The factor $K_0(\gamma)$ is currently being

evaluated, but is certainly of order unity.*

For reasons that are not yet clear the prediction of the surface pressure distribution along the flat surface is much less satisfactory. According to the similarity theory

$$\Delta p/p_{\infty} \approx \frac{0.4 M_{\infty}^2}{(x/d)^{2/3}},$$

and the calculated values are of the correct order within a factor of 1.5 - 2.0. But the final empirical fit to the data⁷ is

$$\frac{\Delta p}{p_{\infty}} = 0.0161 \frac{M_{\infty}^3}{(x/d)^{0.5}}$$

in the range $4 \times 10^3 \leq Re_d \leq 70.6 \times 10^3$. Bertram⁹ measured pressure distributions for a similar geometry in the 11 x 11 inch heated air tunnel at the NACA Langley Laboratory at $M = 6.86$, and his data for $Re_d = 1960$ show an inverse $2/3$ power dependence on x/d in the range $10 < x/d < 70$ (approx.). However, the range of over-pressures and leading-edge thickness is not wide enough to permit any definite conclusions to be drawn.**

For thinner leading-edges the effects of boundary layer-external

* For the constant energy flows ($m = \frac{2}{3+k}$) solutions of the equations of motion are obtained in closed form. This property was discovered first for the spherical (Taylor) case by R. Latter⁸, but it holds also for axially-symmetric and planar flows.

** Unfortunately most of the considerable body of data on shock shapes for blunt-nosed bodies of revolution falls in the range where the parameter $\frac{\gamma-1}{2} M_{\infty}^2 \theta_s^2$ is of order $1 \rightarrow 2$, or less. An experimental study of the hemisphere-cylinder is now in progress at GALCIT in the $M = 7.8$ air tunnel.

flow interaction are clearly discernible in the Princeton experiments.⁷ The question naturally arises as to the relative importance of the inviscid pressure field associated with the blunt leading-edge and the self-induced pressure generated by boundary layer growth. An estimate of the relative magnitude of these two effects can be obtained by considering the energy introduced into the transverse flow field by the blunt leading-edge and by the pressure drag, D_V , associated with the "effective" body shape. The quantity D_V is given by

$$D_V = l \cdot \rho_\infty u_\infty^2 \frac{M_\infty^{3/2} C^{3/4}}{(Re_l)^{3/4}} \left(\frac{4p_o \cdot \delta_o}{\gamma} \right)$$

according to the strong interaction theory¹⁰, and the nose drag is comparable with D_V when

$$l/d = \left(\frac{\gamma}{8p_o \delta_o} \right)^4 \left(\frac{Re_d}{CM_\infty^2} \right)^3 \approx \frac{1}{15} \left(\frac{Re_d}{M_\infty^2} \right)^3$$

for both helium and air. Thus at $M_\infty = 15$ the viscous interaction effects should be important for $Re_d < 10^3$, but somewhere in the range $1500 < Re_d < 2000$ the inviscid effects must spread rapidly over the plate surface, and certainly for $Re_d > 3000$ the inviscid pressure field is dominant and determines the boundary layer development, skin friction and heat transfer over the forward portion of the body. These rough estimates are in qualitative agreement with the experimental results of References 7 and 9.

The author would like to express his appreciation to Dr. Julian D. Cole for stimulating and helpful discussions of this problem.

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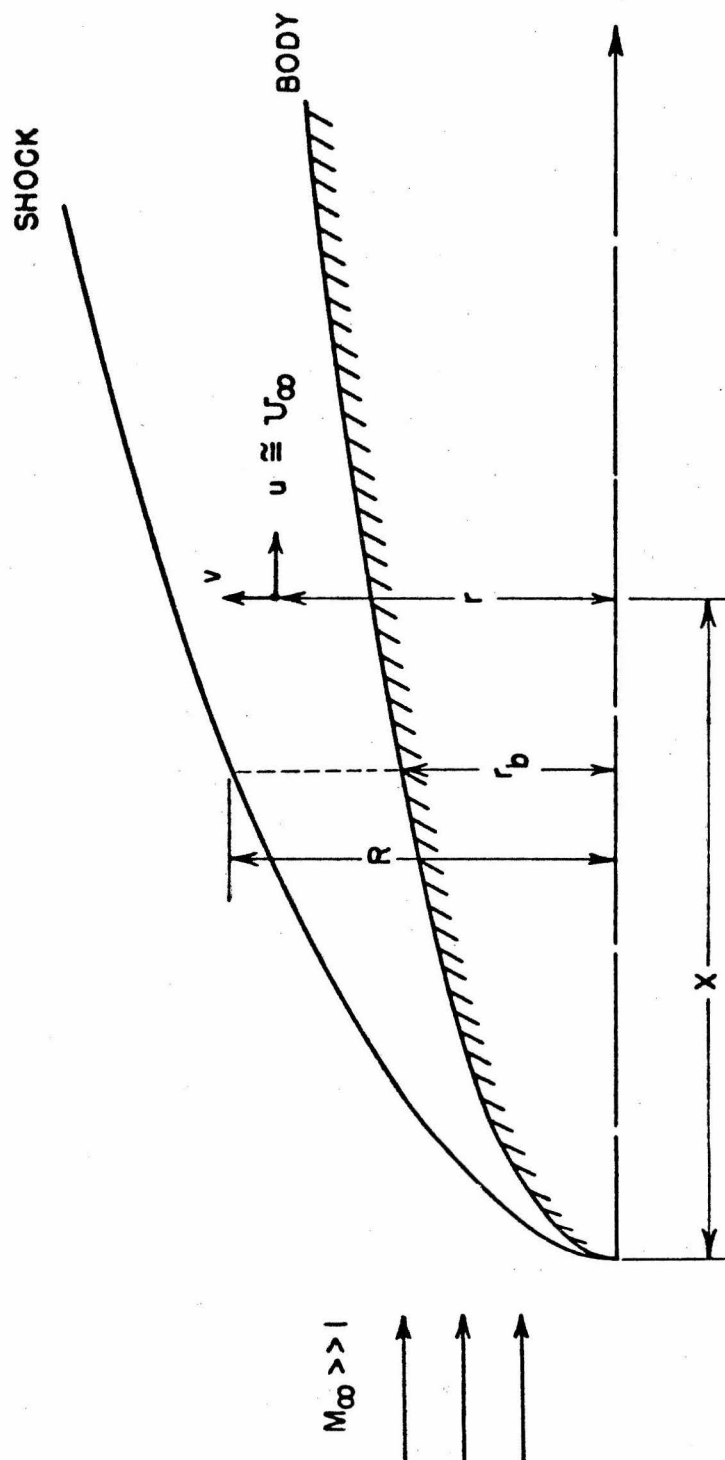


FIG.1 - HYPERSONIC INVISCID FLOW OVER A BLUNT-NOSED
SLENDER BODY

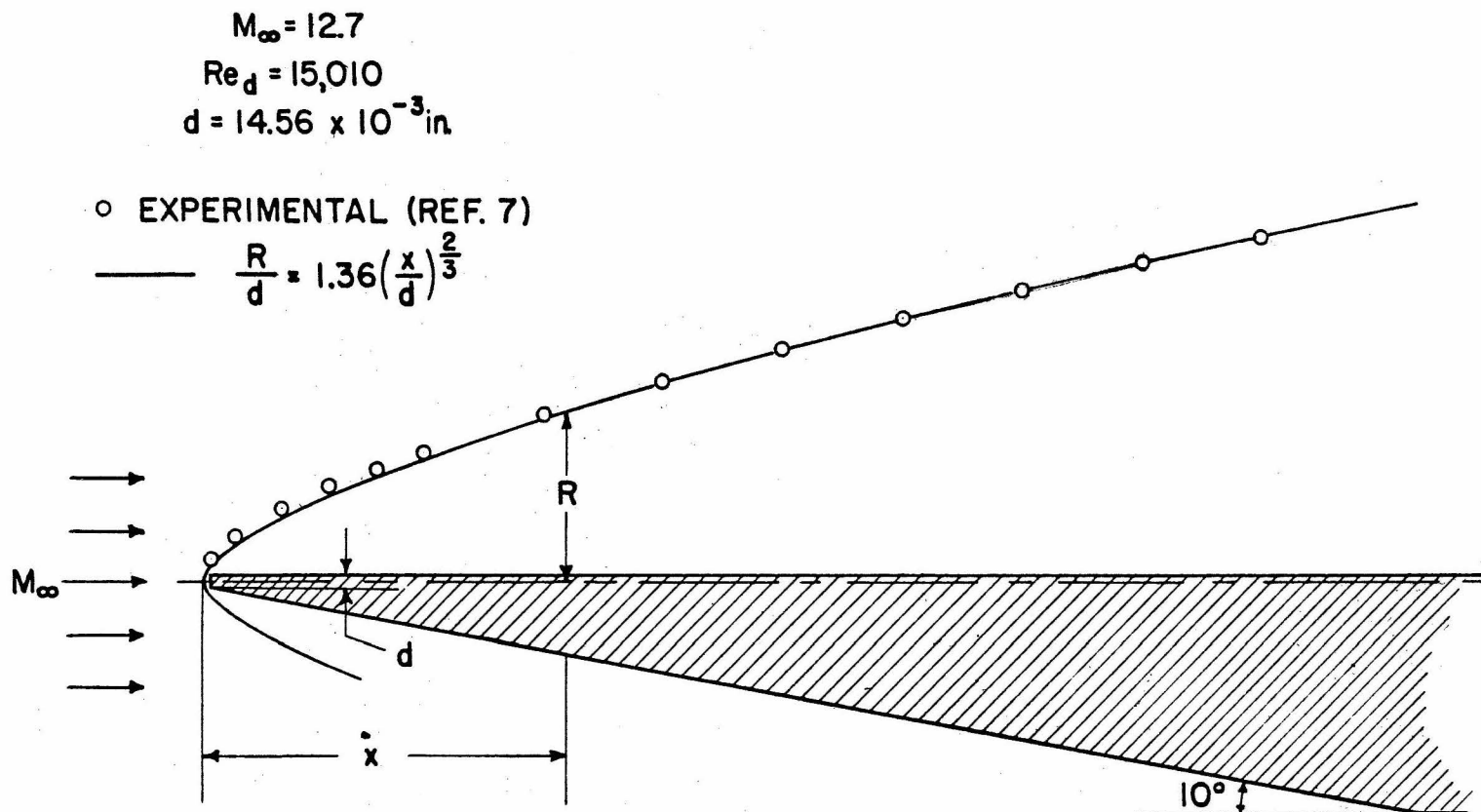


FIG. 2 SHOCK WAVE SHAPE FOR FLAT PLATE WITH BLUNT LEADING EDGE

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